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OCEAN CIRCULATION AND FRONTS AS RELATED TO
ICE MELT-BACK IN THE CHUKCHI SEA

BY

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Ocean Circulation and Fronts as Related to Ice Melt-Back in the Chukchi Sea

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In summer at the edge of the retreating ice pack in the Chukchi Sea, a sharp temperature and salinity front is formed as the result of ice melt by warm surface water from the south. Beneath this front another front is present, formed from the juxtaposition of the resident winter bottom water under the ice and a water transitional between it and warm summer water flowing northward from Bering Strait. The two fronts may be coincident where the current shears parallel to the ice with low to moderate lateral mixing. They may also be widely separated in areas where the current impinges normal to the ice, most often within ice embayments. On the flanks of rapidly moving streams, wedge-like frontal interfaces in the lower layer are likely to be found. These fronts are often rich in temperature fine structure. The ice melt-back patterns and the various frontal arrangements appear to be controlled by steering of the currents by bottom bathymetry.

INTRODUCTION

Six summer cruises, in 1971, 1972, 1974, 1975, 1977, and 1978, on U.S. Coast Guard icebreakers, were made to the marginal sea-ice zone (MIZ) of the shallow Chukchi Sea (Figure 1) as part of the MIZPAC Project. The primary objective of these cruises was the study of temperature fine structure [see e.g., *Paquette and Bourke,* 1979*a*], but also evident in the data are some interesting behaviors of the temperature fronts which occur near the ice margin and of the circulations which cause them.

The marginal sea-ice zone may be described as that zone in which the evidences of interaction of ice and warm water are notable. Within this zone, near-surface fronts are found all along the ice edge and are especially apparent during summer when active melting of the ice produces a sharp lowering in the temperature and salinity of the warm southern water which impinges on it. Lower layer fronts of exceeding variety and complexity are also found in the vicinity of the MIZ, the result of interaction of the cold under-ice water with the warmer water from the south. These are not so widespread as the near-surface fronts and have only been readily identified in the 1977 and 1978 data. *Graham* [1978] first recognized the association of several types of fronts with the circulation pattern within the MIZ. This association was further tied to the shape of the ice edge by *Paquette and Bourke* [1978] who postulated that bathymetric steering of the warm southerly water caused the ice edge to recede annually in an irregular but repeatable manner. It is the purpose of this paper to clarify further the circulation pattern, reaffirm its association with bathymetry and with ice melt-back patterns, and to discuss the various types of fronts between warm southern water in the Chukchi Sea and the cold water under the ice.

MEASUREMENTS

The data upon which this discussion is based were all obtained from the central and eastern Chukchi Sea in July and August in various years and are presented in a series of reports by *Paquette and Bourke* [1973, 1976, 1978, 1979*b*) and a thesis by *Zuberbuhler and Roeder* [1976]. These data comprise a total of over 800 stations, many of which are at 2–10 km spacing on lines normal to the local ice margin. The earlier data, through 1974, were obtained with Bissett-Berman salinity-temperature-depth (STD) recorders, modified with a special adaptation to permit measurement at low salinities. The later data were obtained with the Applied Physics Laboratory, University of Washington (APL-UW) conductivity-temperature-depth (CTD) recorder [*Becker,* 1975]. Information pertinent to each cruise is listed in Table 1.

A large but scattered array of historical salinity-temperature data in the area, taken with reversing bottles, was not considered for the present purposes, principally because the station spacings were too large to locate and characterize fronts clearly and because many of the data were confined to ice-free areas. Further, the data are accompanied by little or no information regarding the location of the ice edge. These data have been well used by workers such as *Coachman et al.* [1975], hereinafter designated CAT, in establishing the general oceanography of the area. Also not used are three sets of data taken by APL-UW in 1971, 1972, and 1973 with their CTD [*Garrison and Pence,* 1973; *Garrison et al.,* 1974; *Garrison and Becker,* 1975]. These data tend to be over the Barrow Canyon, in the western Beaufort Sea, or they were taken from a drifting ice station wherein the station distribution does not lend itself to the present problem. *Garrison and Becker* [1975] also report a duplicate set of measurements taken simultaneously with ours on the same ship in 1974 with their CTD. We have used these to some extent to check our 1974 data.

We have tended to prefer the data from MIZPAC 1974, 1975, 1977, and 1978 because (when supplemented with the Garrison and Becker data of 1974) they reach to bottom, something which could not be achieved satisfactorily with the STD, and the station distributions are somewhat more logical than in the earlier cruises. However, the earlier data are used where appropriate.

GENERAL ICE CONDITIONS

The southern portion of the Chukchi Sea is ice-covered for nearly 8 months of the year, and the ice remains south of 71°N for 10 or 11 months. The ice begins to disappear at Bering Strait in about late June, after which melting is rapid under the influence principally of the warm (6°–10°C), northward flowing water, probably not much modified since leaving Bering Strait [*Paquette and Bourke,* 1979*a*]. The ice reaches its maximum retreat at approximately 72°–75°N latitude in mid-September [*Potocsky,* 1975, p. 65]. At Bering

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Fig. 1. A map of the MIZPAC area. The arrows suggest steering of the broad northward flow through the various troughs and canyons which channel it into streams melting embayments in the ice. Also implied is bathymetric steering of the Alaskan Coastal Current along the 20-fathom isobath north of Cape Lisburne and subsequent branching along the 30-fathom isobath northwest of Barrow. Bottom contours are in fathoms (1 fm = 1.83 m). Adapted from NOS chart 16003.

Strait there is a predominantly northerly flow of water, warm, rapid, and less saline in the eastern surface and cold, slow, and more saline in the western bottom (CAT, p. 48ff). These waters develop into a fairly complex group of streams carrying water ultimately northward past the ice. It is the complex nature of these flow patterns which creates the great variety in the ice melt-back pattern.

The ice pack near the margin has great variability. In midsummer in the Chukchi Sea it is usually composed of a mixture of broken eroded blocks and small floes. Sometimes the edge is diffuse, with ice concentrations of less than one okta (one eighth). (Beginning January 1, 1980, the standard reporting unit for ice concentration was changed by the Naval Polar Oceanography Center from oktas to tenths, but the older unit is used here because the data were taken in that form.) At other times, depending upon the wind speed and direction, the concentration may be greater than 6 oktas. Even when the ice is fairly diffuse, the edge tends to be well defined, although there may be isolated blocks of ice in concentrations much less than 1 okta for several kilometers south of the edge. We believe that such concentrations can affect the water properties and also provide evidence of southward drift or diffusion of the ice margin. Concentrations less than 1 okta are not normally reported. We have estimated low concentrations as the reciprocal of the square of the average ice block spacing measured in mean block diameters.

The shape of the margin is irregular, although there are predictable, repeated features, and there are large local differences in ice concentration. The margin is indented by bays of various sizes, some of them similar from year to year and caused by a characteristic water circulation, which is to be discussed below. However, the wind is continually modifying the distribution of the ice; hence the bays produced by the melting action of warm water streams may easily be modified or closed by the wind-driven drift of the ice.

CIRCULATION WITHIN THE MIZ

The Chukchi Sea is a shallow sea with a mean depth of 40–50 m, having gentle knolls and several troughs which are shallow but with a relief which is a substantial fraction of the mean depth. The Barrow Canyon parallels the coast of Alaska and heads far back on the shelf; Herald Canyon, at about 175°W, also has a shallow trough much less notable than the Barrow Canyon. These features are shown in Figure 1. Also shown are lines and arrows indicating the paths of various filaments of flow. All of these follow troughs in the sea floor or other bathymetric features. Two of these flow paths have already been well demonstrated by CAT; the remainder are to be demonstrated in a subsequent section.

The circulation within the Chukchi Sea is known only in the most general fashion, having been inferred by CAT principally from water mass studies reinforced by infrequent, short-term current-meter measurements with some support from concepts of bathymetric steering. In general, CAT show warm water entering the Chukchi Sea through the eastern side of Bering Strait, flowing northward and then west-northwest in a broad stream, starting from south of Pt. Hope, along the two most southerly lines of Figure 1. Near shore, a northeasterly stream branches from this flow in the vicinity of Cape Lisburne. The westerly branch enters the Arctic Ocean by way of the head of Herald Canyon just east of Herald Island. The northeasterly branch narrows into a high-speed jet-like

TABLE 1. MIZPAC Cruise Summary

	1971	1972	1974	1975	1977	1978
Cruise dates	July 30 to August 20	July 31 to August 19	July 13–30	July 30 to August 14	July 24 to August 6	July 14–28
Ship	USCGC *Northwind*	USCGC *Burton Island*	USCGC *Burton Island*	USCGC *Glacier*	USCGC *Burton Island*	USCGC *Glacier*
Stations occupied	163	114	111	194	157	130
Instruments	Bissett-Berman 9006 STD	Bissett-Berman 9006, model 1 with 200-ft depth scale	Bissett-Berman 9006, model 1 with 200-ft depth scale	APL-UW portable CTD	APL-UW portable CTD	APL-UW portable CTD
Reference	*Paquette and Bourke* [1973] NPS-58PA73121A	*Paquette and Bourke* [1973] NPS-58PA73121A	*Paquette and Bourke* [1976] NPS-58PA76051	*Zuberbuhler and Roeder* [1976] NPS-58PA76091	*Paquette and Bourke* [1978] NPS68-78-001	*Paquette and Bourke* [1979] NPS68-79-003

stream approximately along the 20-fathom isobath north of Cape Lisburne and then close to the Alaskan Coast between Wainwright and Pt. Barrow, where it flows eastward into the Beaufort Sea. We have called this stream the Alaskan Coastal Current (ACC) [*Paquette and Bourke,* 1974]. This warm stream probably is the principal cause of the melting of the shore lead along the northwestern Alaskan coast.

Hypotheses

The conclusions of CAT regarding the general circulation may be expanded considerably by recognizing that the major recurring bays in the ice margin are produced by the melting action of warm water streams. As has been mentioned, *Graham* [1978] first proposed this theory, and his conclusions are supported and expanded here. The arguments for this theory are summarized as follows.

1. The bays recur from year to year in approximately the same places. This will be seen in the MIZPAC data soon to be presented, but it is also evident in the ice maps derived from satellite observations and issued by the Naval Polar Oceanography Center, Suitland, Maryland. Figure 2 is redrawn from four such maps superimposed. The dates are chosen to catch the ice margin in approximately the same position. Four major melt-back features may readily be seen. There is a large bay at 170°–175°W, another centered at about 168°W, the shore lead along the Alaskan coast, and an embayment generally west to WNW of Pt. Barrow. The western-most of these bays is undoubtedly due to the main northwesterly flow mentioned by CAT, and the shore lead is due to the Alaskan Coastal Current.

It is remarkable that these bays persist year after year in the same locations in spite of the influence of varying winds, differing rates of inflow of ice from the north, and climatic differences which influence not only water temperatures but also the rate of flow through Bering Strait. They must be due to powerful, well-defined influences and cannot be due to continually changing effects such as the wind stress.

2. Each of the bays, except the one west of Pt. Barrow, is sufficiently near to a trough in the shallow sea floor that bathymetric steering may be invoked as a mechanism for concentrating and directing the flow (Figure 1). The bay west of Barrow may be caused by the steering action of the westward curving left bank of the Barrow Canyon as it encounters the continental slope to the north.

3. Measurements along the axes of the bays show warm water in thicknesses of approximately 10 m penetrating northward nearly to their apices. The bays, therefore, cannot be due to jets of water or ice flowing southward. If they were, the water in the bays would tend to be cold, and they would tend to be filled with brash ice.

Warming of a bay, otherwise cold, by solar and atmospheric heating is not a satisfactory explanation. A water column 10 m thick would be warmed roughly only by 200 Ly/day or 0.2°C per day [*Huyer and Barber,* 1970]. However, at the same time, an unwarmed sea surface is being created at a rate of about 10 km/day by the general northward ice recession. A bay 150 km long would be in situ only long enough to be warmed to an average temperature of 1.5°C, much colder than the observed temperatures within the bay.

It would also be conceivable that ice moving southward forms the peninsulas, leaving warm water in between. However, there seems little reason to believe that such drifts should be in the form of bands of ice steered along ridge crests in the bathymetry.

4. Adequate heat and northward water flow to melt the ice probably exists to the south. The water a short distance south of the ice is remarkably warm. The upper 10 m has temperatures of 6°–10°C, and there is additional heat in the lower 40 m. Under the ice, temperatures below freezing usually prevail. Thus, there is sufficient heat in the southern water to melt back the average 1 m of ice thickness at the margin at a rate about half the velocity of impingment of the warm water upon the ice, provided the 6000–10,000 calories of heat in the upper layer can all be utilized to melt ice. This latter condition must be true since little of this heat extends more than a few kilometers behind the ice edge. The 1.5 Sv of northward flow through Bering Strait, if averaged over the width and depth of the Chukchi Sea at 70°N east of Wrangel Island, would move water northward at about half the mean melt-back rate of 10 km/day. Concentration of the flow into filaments and into the upper layer could easily provide the velocities necessary to melt out the bays.

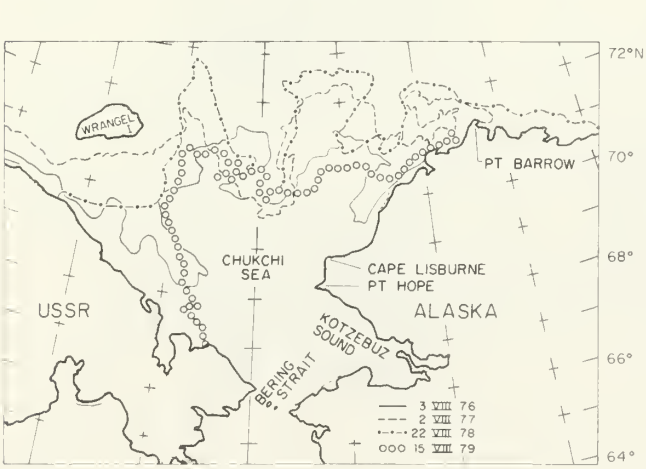

Fig. 2. A composite map of the ice edge for 4 years redrawn from maps routinely issued by the Naval Polar Oceanography Center, Suitland, Maryland. Note the consistent formation of bays and the shore lead to the east melted out by the warm northward-flowing current.

Observational Support

Some of the above statements are illustrated by ice margin and temperature data from the six MIZPAC cruises shown in Figures 3–8. These figures also show fronts and fine structure locations, which are to be discussed later. The temperatures shown are the maximum temperature in the water column which usually corresponds to the surface temperature but still continues to indicate the presence of heat in the few cases when the warm water is overlain by 3–10 m of cold melt water. The ice margin positions are derived principally from shipboard observations but supplemented to some extent by the satellite-derived maps of the Naval Polar Oceanography Center.

The persistence of the several bays and of the shore lead previously mentioned is easily seen, as is the penetration of heat northward into the bays. Figures 4, 7, and 8 from MIZPAC 1972, 1977, and 1978, show the bay at 168°W, the shore lead, and the bay west of Pt. Barrow, respectively, all well developed. It is also possible to see a minor indentation at 163°W which may correspond to a stream steered by the trough at

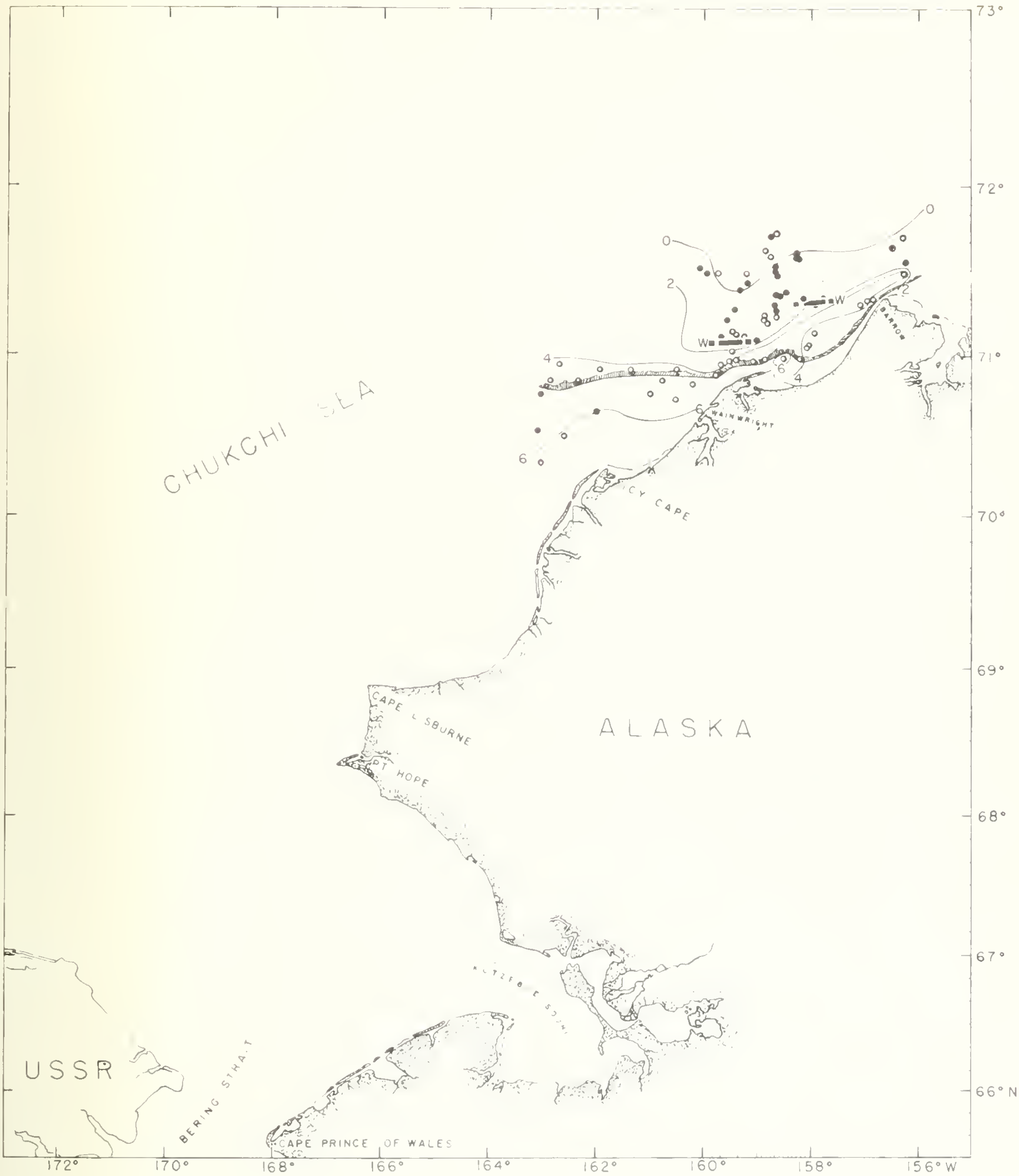

Fig. 3. A plot of the station distribution for the MIZPAC 1971 cruise showing the positions of the ice edge and contours of the maximum temperature in the water column. Open circles indicate stations having temperature fine structure of less than 0.5°C peak-to-peak, solid circles greater than 0.5° C. The location of upper-layer fronts is denoted by a solid rectangle, lower-layer fronts by solid squares, where they are coincident by solid square, rectangle, square, and followed by a W or a V if the lower layer is wedge-like or vertical, respectively.

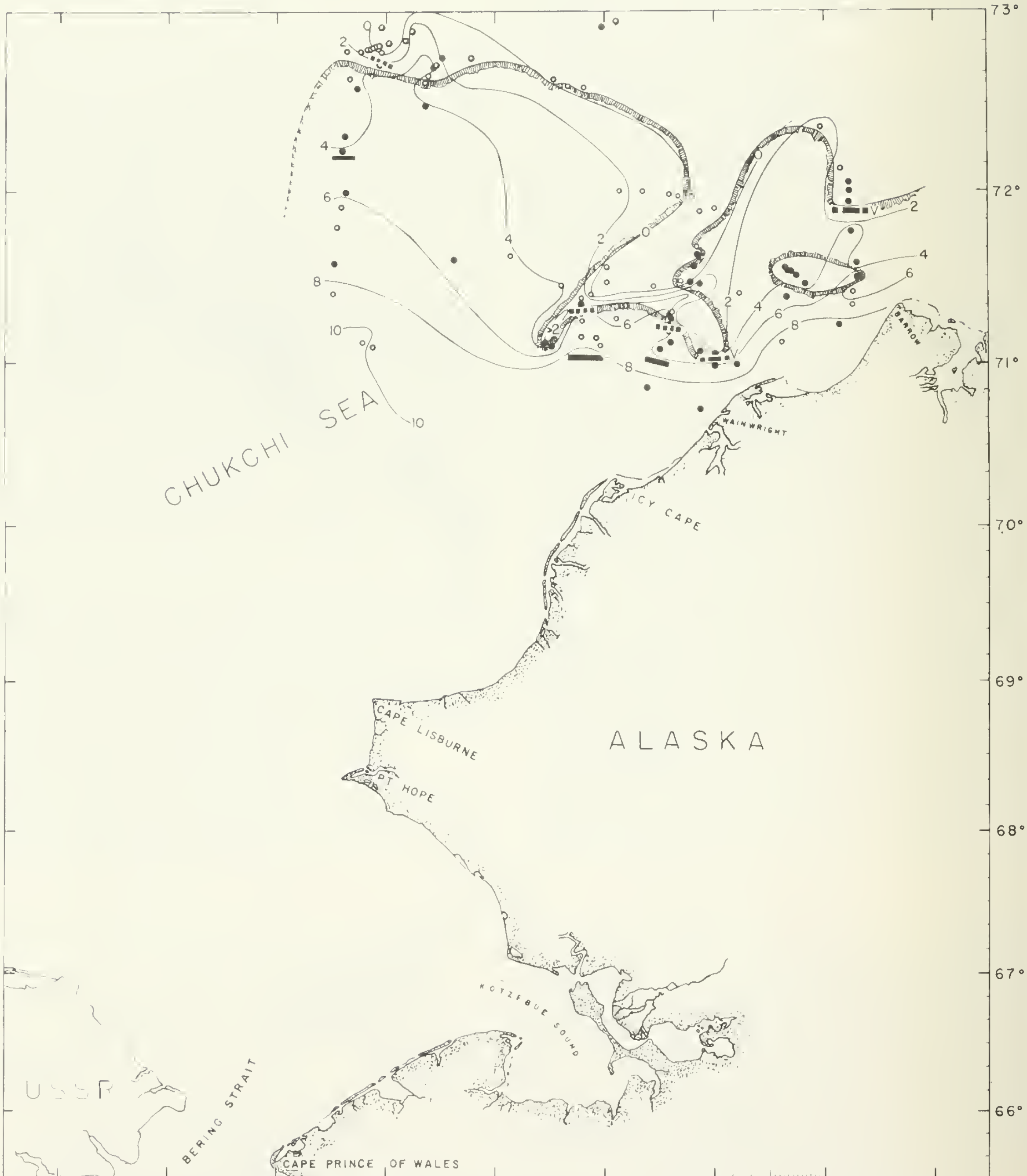

Fig. 4. Station distribution for the MIZPAC 1972 cruise. Contours and symbols are the same as in Figure 3.

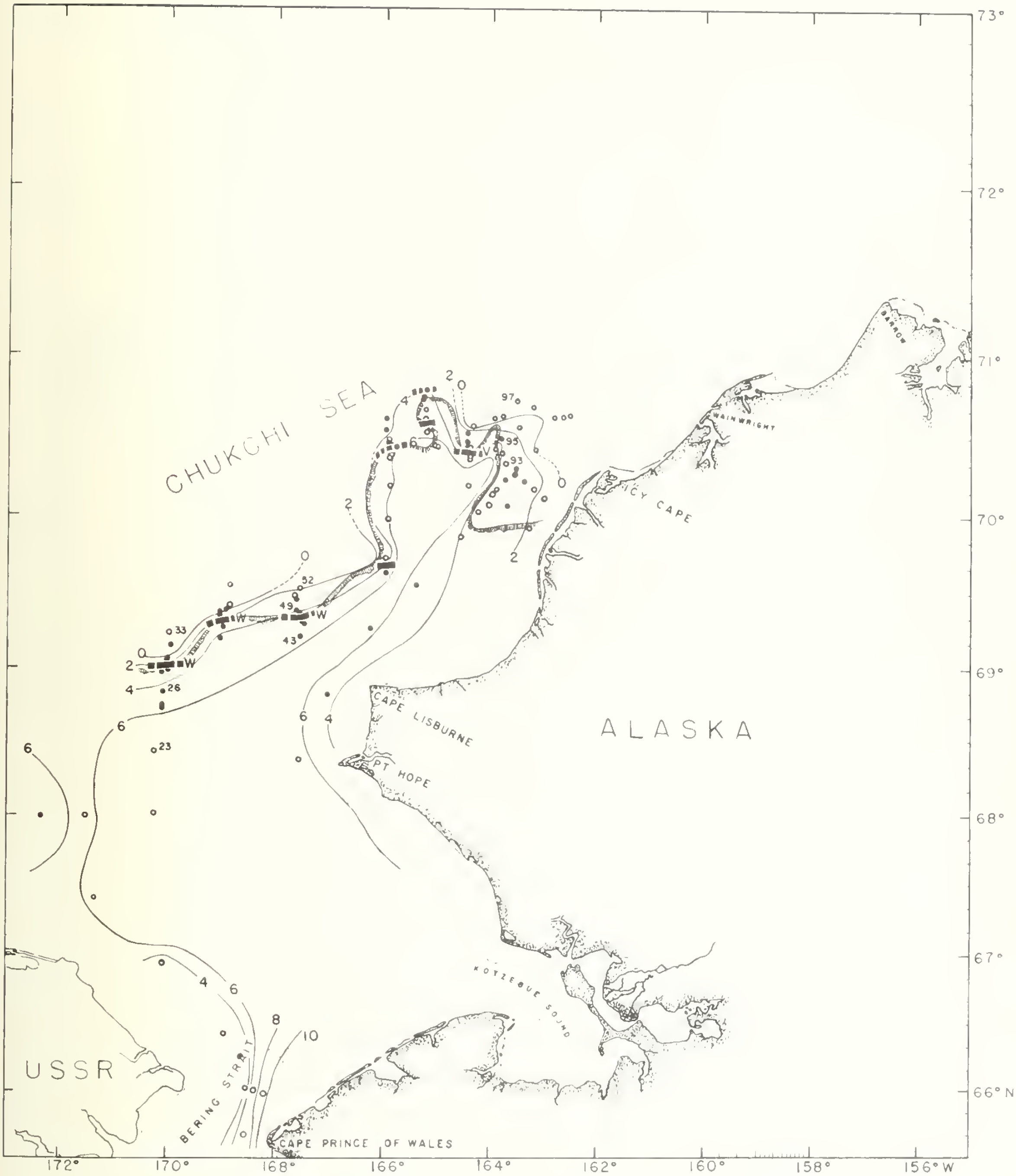

Fig. 5. Station distribution for the MIZPAC 1974 cruise. Contours and symbols are the same as in Figure 3.

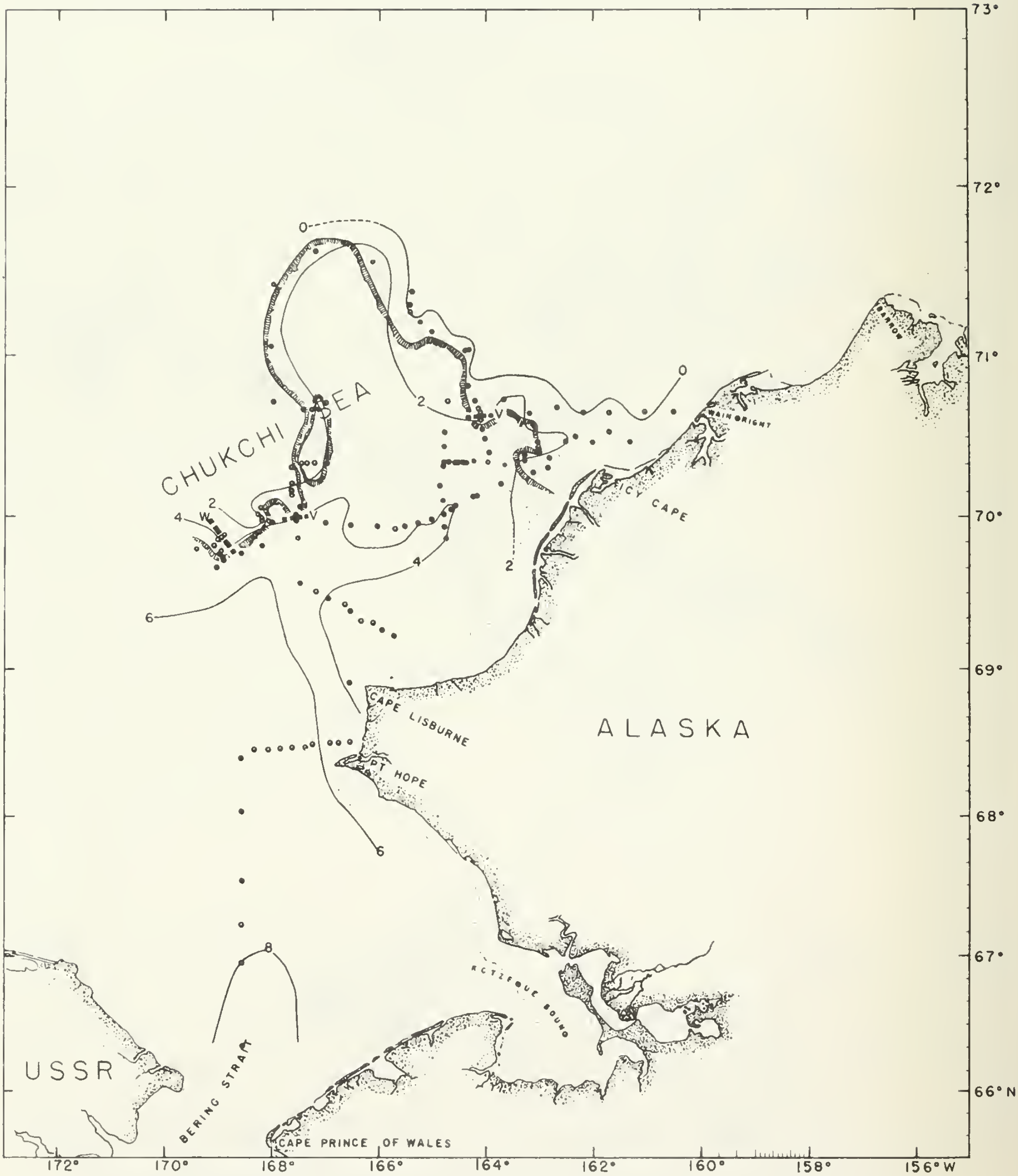

Fig. 6. Station distribution for the MIZPAC 1975 cruise. Contours and symbols are the same as in Figure 3.

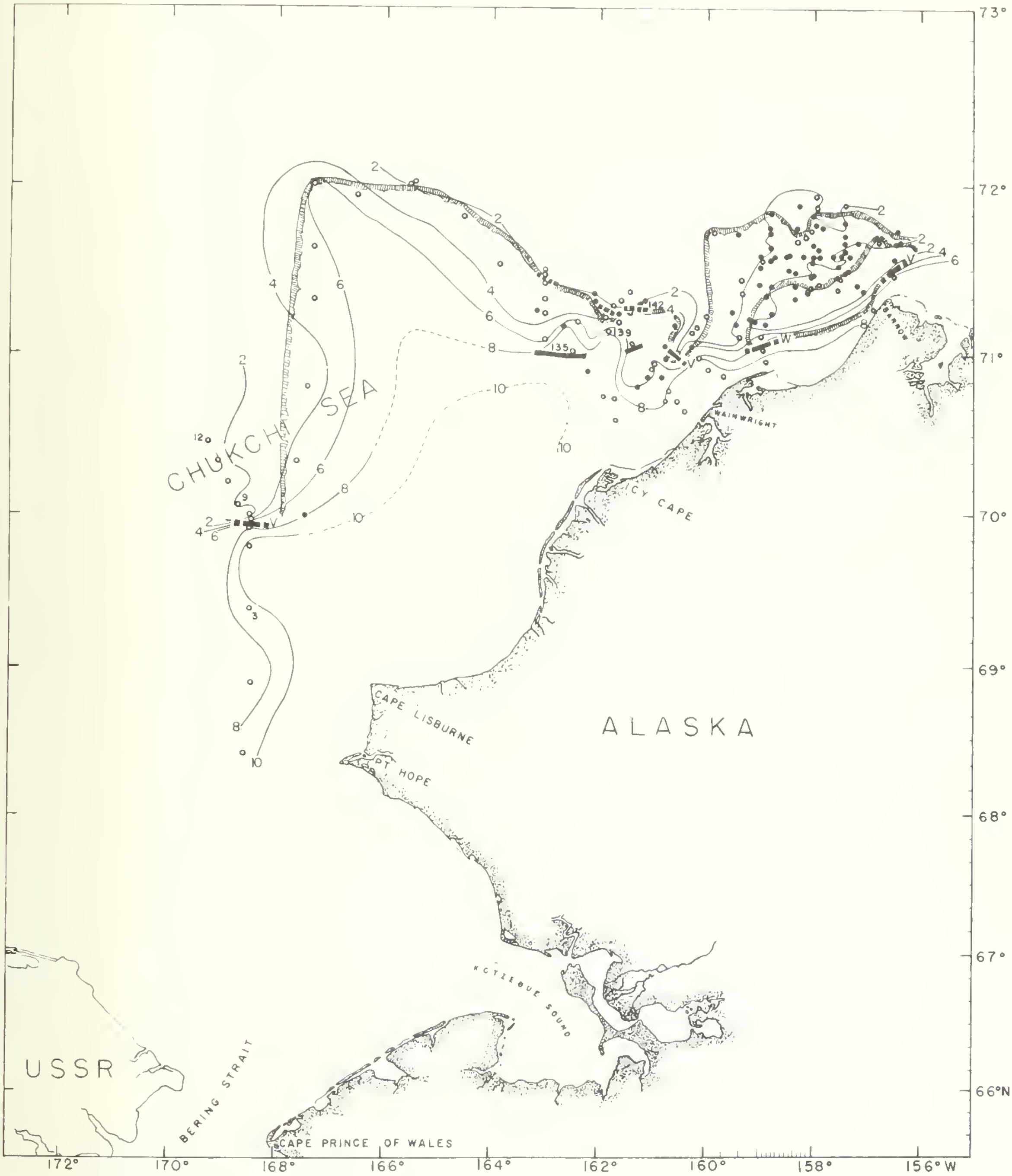

Fig. 7. Station distribution for the MIZPAC 1977 cruise. Contours and symbols are the same as in Figure 3.

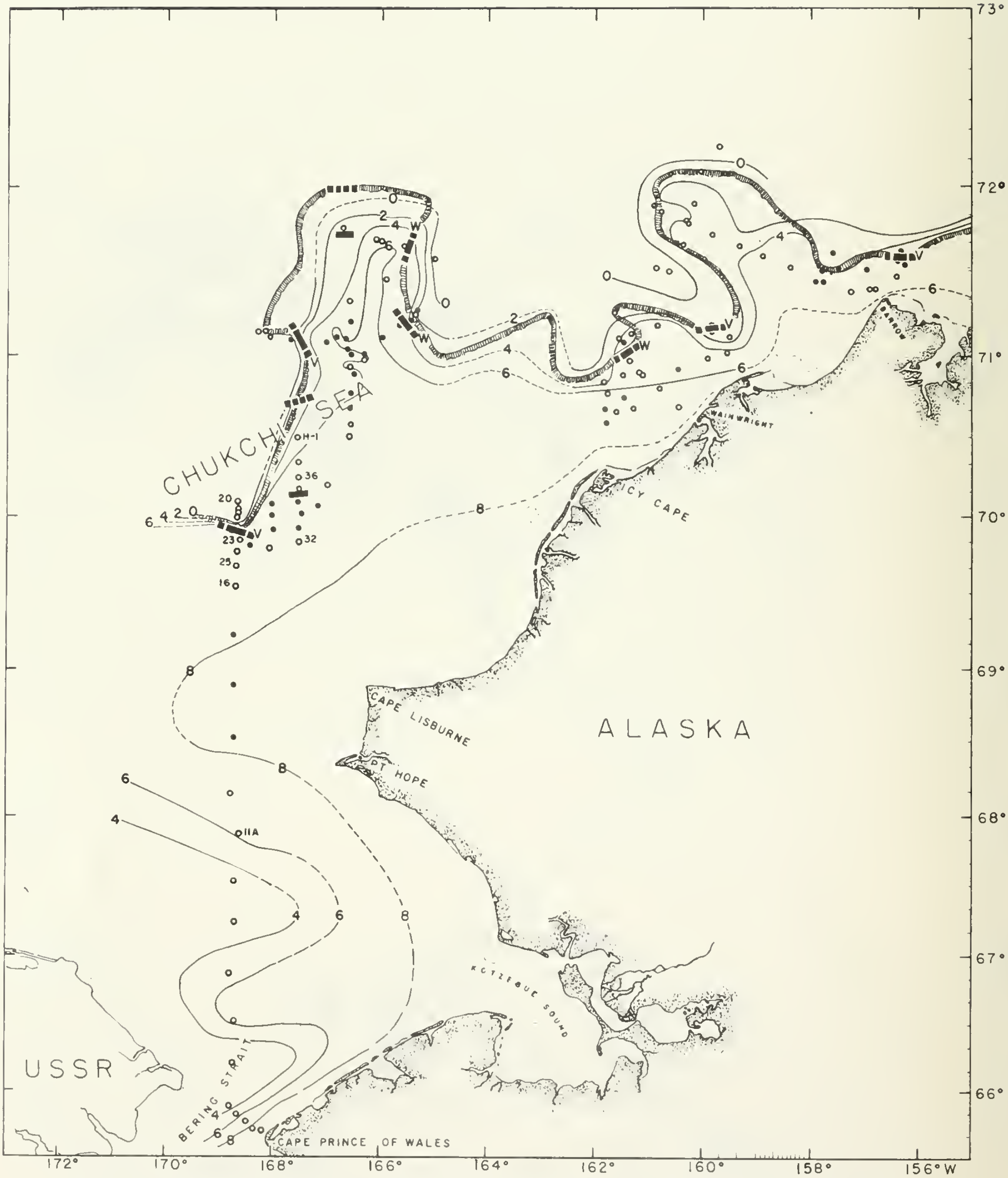

Fig. 8. Station distribution for the MIZPAC 1978 cruise. Contours and symbols are the same as in Figure 3.

that position (Figure 1). There is insufficient evidence to permit speculation on the cause of the weak development of a bay at this longitude.

The ice edge conditions observed in Figure 3, MIZPAC 1971, require extra interpretation. Considerable heat is present north of the reconstructed ice edge. In 1971, the first MIZPAC cruise, ice edge information was poor. The ice was not as tightly packed as usual, and it was not recognized at the time that the ship was probably in the ice bay west of Pt. Barrow amidst large floes in ice concentrations of 0.2–0.7.

MIZPAC 1974 (Figure 5) was the earliest of the MIZPAC cruises. The ice reached south to 69°N. The bay near 165°W is caused by the ACC previously mentioned. The bay at 168°W has not developed because the bathymetric features which steer the corresponding stream of water becomes well defined only 100 km farther north (see Figure 1).

MIZPAC 1975 (Figure 6) was unusual in that 1975 was the worst ice year of record and the shore lead along the coast was too narrow and uncertain for the passage even of icebreakers until September. No information about the ice bay west of Pt. Barrow was obtained. It is likely that bad ice years are due to a shift in the general wind pattern over the Arctic Ocean which drives ice southward [see *Barnett*, 1976]. In spite of the ice pressure from the north, the bay at 168°W is well formed.

In summary, the spatial invariance of the bays, their close association with bathymetric features, and the presence of warm water within them leads to the conclusion that there are a number of bathymetrically steered filaments of northward flow in the Chukchi Sea which melt out the bays. These filaments are (1) the broad westerly to northwesterly flow mentioned by CAT; (2) the Alaskan Coastal Current, also previously known; (3) a flow following the 25-fathom trough north of Cape Lisburne on about 168°W; (4) a minor branch from the ACC north of Icy Cape near 163°W; and (5) a branch of the ACC following the northwestward-turning contours of the left bank of the Barrow Canyon.

FRONTS IN THE MIZ

Fronts found within the MIZ exist in both the upper and lower layers of the stratified water column. These fronts are strongest in temperature but can have appreciable salinity gradients as well. This section describes features associated with each type of front and the circulation pattern which might be expected to produce each type. Before proceeding further, however, it is necessary to present a brief overview of the water masses which participate in the frontal interactions. A detailed analysis of the water mass structure within the Chukchi Sea is presented in CAT, while *Paquette and Bourke* [1979*a*] have discussed the waters found in the immediate vicinity of the MIZ.

Water Masses

Within the central and eastern Chukchi Sea, two major water masses are present in the vicinity of the ice edge, usually separated by a narrow transition zone. At and behind the ice edge is a cold (−1.6° to −1.7°C) saline (32.8–33.6‰) water which we term northern water. This water is near the equilibrium freezing point temperature (always less than 0.2°C above freezing) and is obviously a relic of the previous winter's brine convection, warmed slightly without notable dilution [CAT; *Paquette and Bourke*, 1979*a*]. An upper less dense stratum about 10 m thick may occur with temperatures near 0°C and salinity about 28–30‰ owing to the melting of ice. In zones of active melting, extreme dilution (salinities ranging from 3 to 25‰) may extend to depths as great as 5 m.

For some distance to the south of the ice there is a strongly two-layered southern water of Bering Sea origin (CAT). Temperatures in the upper 5–15 m are usually between 5° and 10°C; salinities range from 30 to 32 ‰. Below an exceedingly sharp thermocline, with gradients frequently as great as 6°–7°C/m, is a layer with small vertical gradients of salinity and temperature. This lower-layer southern water is warmer but less saline than northern bottom water; less than 32.6 ‰ and between about −1.3° and 2°C.

The transition zone is a zone in which the water properties grade from those of southern water into those of northern water. The zone may be of different widths in the upper and the lower layer. When it is narrow, the zone is readily identified by its relatively rapid change of properties. Fortunately, narrow zones and wide zones occur during the same cruise, and it is possible to use the properties of the narrow transition zones to identify the limits of the wide ones.

Some of the preceding descriptions may be illustrated by a temperature-salinity cross section (Figure 9) constructed from data taken along the western-most line of stations during MIZPAC 1978 (Figure 8). The water to the south of the ice is a broad band of sharply layered southern water. Transition begins near bottom about 35 km from the ice and, near the surface, about 8 km from the ice. The northern water is seen almost as a wall, beginning slightly south of the ice. In other years the temperature of northern bottom water may sometimes be warmer and the salinity is usually higher.

Upper-Layer Fronts

During discussion of the fronts, reference will again be made to Figures 3–8. Upper-layer fronts are shown in these figures as heavy dashed lines and lower layer fronts by heavy solid lines. When these two types of front are coincident, the symbolism is a combination of the two. When the lower-layer front is wedge-like, the line is marked by a W and, where it is near vertical, by a V.

The upper-layer fronts are widespread along the ice edge and are caused, as has been mentioned, by the contact of the warm, upper-layer water from the south with the ice. Figure 10, an example of an upper-layer front from MIZPAC 1977 (Figure 7), shows that the isotherms are nearly vertical and that the horizontal temperature gradient can be substantial, 9°C temperature change over 20 km in this case. As in this instance, the upper-layer front need not always be associated with the instantaneous ice edge location as the ice can move faster than the front in response to a changing wind pattern. This can lead to fronts being either behind or outside of the ice edge. In our experience the separation of an upper-layer front and the ice edge is rarely as great as 10 km.

Often a subsurface temperature maximum will be seen in individual profiles. Figure 11 from MIZPAC 1974 (Figure 5) illustrates this feature from a transect across the ice margin. It is the result of warm southern water running under the ice with little vertical mixing so that the top is cooled leaving a warm core beneath the surface. This situation is most often observed within the core of the Alaskan Coastal Current.

Lower-Layer Fronts

The fronts found in the lower layer are perhaps more interesting than are their counterparts in the upper layer. The dynamics involved in their formation are more complex, they

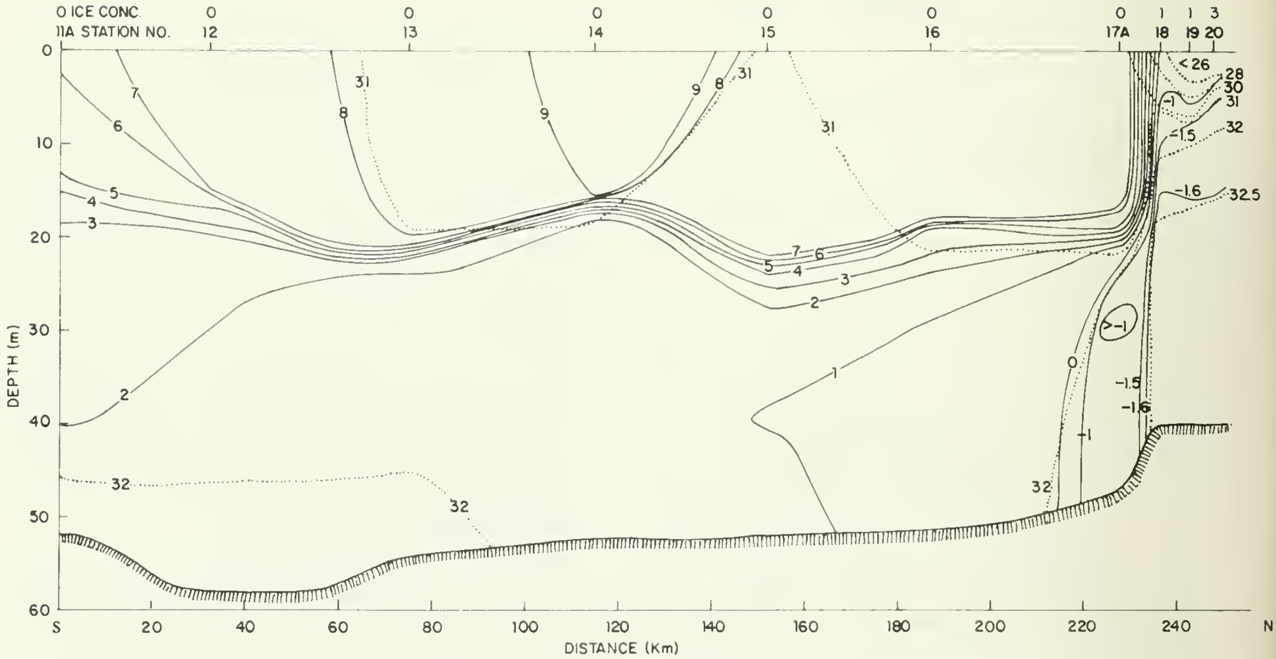

Fig. 9. Temperature and salinity cross section from the westernmost line of stations in MIZPAC 1978 (Figure 8) oriented approximately S-N. Station 18 marks the approximate boundary between warm southern water to the left (south) and cold northern water to the right (north). Closed isotherms indicate regions of imbedded fine structure. The ice concentration is in oktas (eighths). Note that the salinity field is closely representative also of the density field at these low temperatures and relatively large salinity gradients.

are of several types, and it is these fronts which are associated with large scale temperature finestructure [*Paquette and Bourke,* 1979*a*].

Lower-layer fronts mark the contact boundary of lower-layer southern water with lower-layer northern water. Both of these waters are usually modified from their parent water types to form a transition zone within which frontal juxtaposition occurs. The lower-layer fronts have been categorized into three types based on their positions with respect to the upper-layer front: vertical coincident, widely separated, and wedge-shaped fronts. The characteristics of each type are discussed below.

Vertical coincident fronts. Vertical coincident fronts are one of the most striking features of the MIZ. The term 'vertical' here implies a frontal slope of 5–25 or more m/km. Here a temperature front and usually a weaker salinity front extend from the sea surface to the sea floor; the position of the upper-layer front coincides with the lower-layer front. Figure 12 illustrates this sharp boundary between southern and northern water in MIZPAC 1977 (Figure 7). One vertical coincident front was first observed in the MIZPAC 1975 data but, probably owing to changes in sampling scheme, such fronts are found more frequently in the 1977 and 1978 data.

Examination of Figures 3–8 indicates that vertical coincident fronts are generally found in close proximity to the ice and in the vicinity of an ice peninsula. Since the ice peninsulas often result from bathymetric steering of the currents on both sides, there is an apparent geographic preference for the location of peninsulas and hence fronts of this type. For instance, one (e.g., Figure 13) is found near the ice peninsula off Wainwright in 1972, 1977, and 1978 and another (e.g., Figure 12) at the edge of the large western embayment near 168°W in 1975, 1977, and 1978.

The feature common to vertical coincident fronts is their location at ice edges which are receding at relatively slow rates and where the transition zone is narrowest, evident by the strong horizontal gradient in T_{max}. These fronts, occurring as they do in a stagnant zone in the 'vee' of a current split, must not be subjected to much lateral shearing and mixing; hence interleaving of waters across the frontal boundary is minimal resulting in temperature finestructure being very weak or absent in these areas. The existence of an ice peninsula at such points is evidence that turbulent action of the oncoming warm water on the ice and the water below it is minimal.

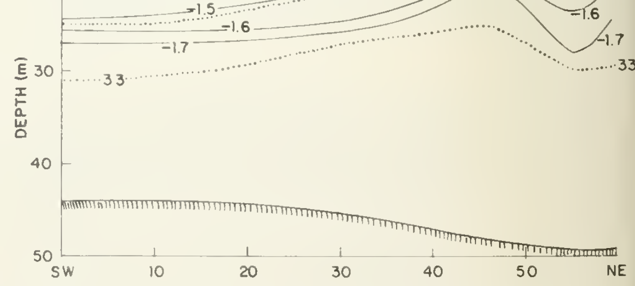

Fig. 10. Temperature and salinity cross section from MIZPAC 1977 (Figure 7) illustrating the upper-layer front. The lower-layer front is approximately 20 km farther southwest of station 135. The ice concentrations are in oktas (eighths).

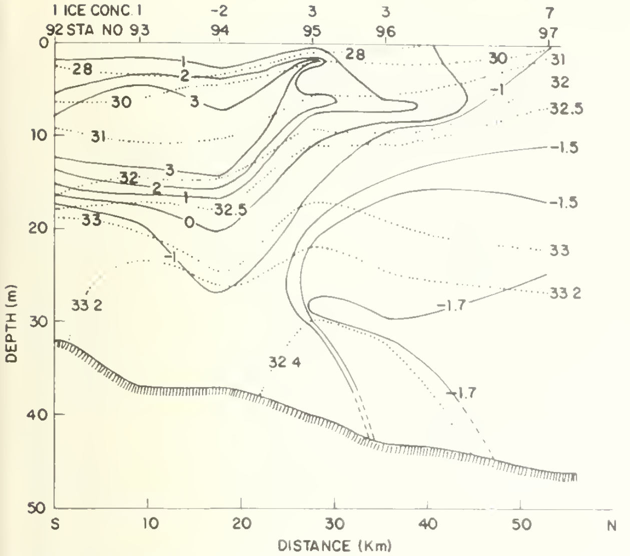

Fig 11. Temperature and salinity cross section from MIZPAC 1974 (Figure 5) showing the upper-layer front submerged beneath a cool, dilute surface layer of melt water. Ice concentrations preceded by a minus sign indicate concentrations in negative powers of ten; positive numbers represent ice concentrations in eighths.

Widely separated fronts. In sharp contrast to the vertical coincident front, there are regions where the upper and lower-layer fronts are widely separated. Figure 10 from MIZPAC 1977 shows that the upper-layer front is at the ice edge and that the lower-layer front, defined by the intersection of the $-1.6°$ to $-1.7°C$ isotherms with the sea floor, must be more than 40 km farther south of the ice. Extrapolating from adjacent stations, the lower-layer front is perhaps another 20 km beyond the most southerly station of this transect. Another example, from MIZPAC 1978 (Figure 14), illustrates a similar situation in which the edge of only the lower front can be seen. A well-defined lower-layer front is observed near station 35, but the upper front is beyond the northern-most station, H-1, perhaps another 20 km farther at the ice edge, a displacement of about 60 km.

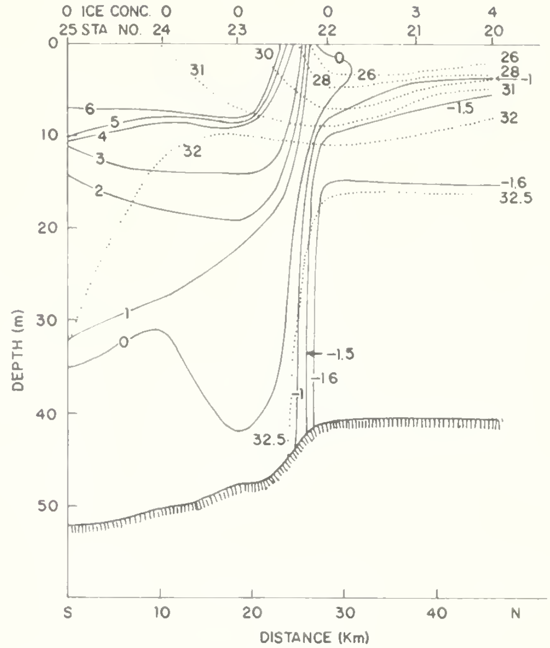

Fig. 13. Temperature and salinity cross section from the line of stations 5 km east of those shown in Figure 9, MIZPAC 1978. The vertical coincident front is present in both temperature and salinity.

The geographic distribution of the widely separated fronts is not so well defined as the vertical coincident fronts. However, they do appear to be in areas of more rapid ice recession, frequently in or near embayments. This is perhaps best observed in the 1977 and 1978 data, Figures 7 and 8. Note that the lower-layer front is generally well south of the ice edge.

We think the reason for the presence of a vertical coincident frontal situation in one place and widely separated fronts in another lies in the nature of the flow at the frontal bound-

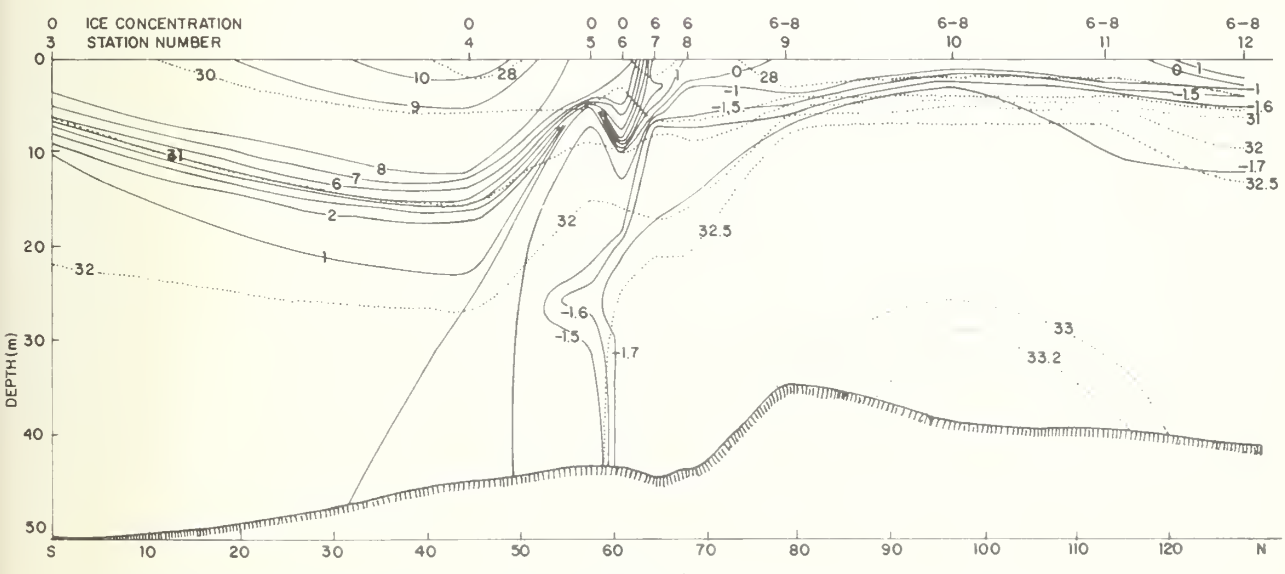

Fig. 12. Temperature and salinity cross section from the westernmost line of stations in MIZPAC 1977 (Figure 7) illustrating the near vertical coincidence of the upper- and lower-layer fronts.

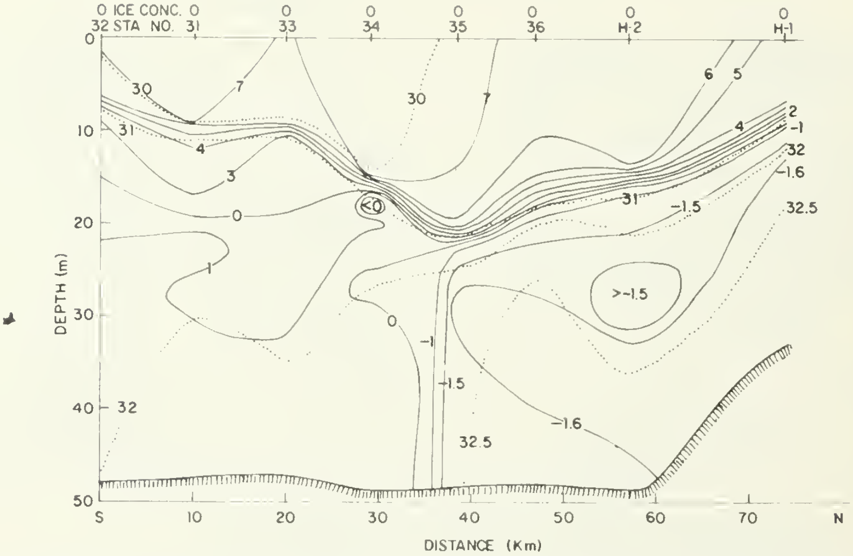

Fig. 14. Temperature and salinity cross section from the line of stations along the western edge of the embayment near 168°W, from MIZPAC 1978 (Figure 8). The lower-layer front is near station 35, while the upper-layer front (not shown) is near the ice edge, approximately 20 km north of station H-1, a station taken from a hovering helicopter.

ary. When the flow is a weak shear parallel to the northern water and the ice margin, ice is sheared away by melting in the upper layer and northern water is sheared away by the lower layer. Mixing products are carried away downstream, even though the flows are slow, and the modified water is not seen along a line normal to the flow and to the ice. Likewise, any displacement between the upper layer and lower layer owing to different speeds of advance is not visible.

When the southern water approaches the ice more or less perpendicularly, as it does when a bay is formed, the advancing front of southern water is visible in a section along the axis of the bay and the slower speed of the lower layer is evidenced by the displacement of the lower-layer front to the south. This lower speed of the lower layer is to be expected not only because the layer is frictionally retarded by bottom but also because the warm, less saline upper layer is fed by the warm flow through the eastern side of Bering Strait which carries a large proportion of the total transport (CAT, Figures 31 and 48).

Wedge-like fronts. Fronts which do not clearly belong to the previous two categories are lumped together under the description, wedge-shaped, for want of a better term. The examples which led to this naming come from the three westernmost ice crossings of 1974 (Figure 5) of which the first and third are shown as Figures 15 and 16. The base of the slope of northern bottom water is approximately coincident with the ice edge and the upper-layer front; the face of the northern bottom water slopes upward at a moderate angle toward the interior of the ice pack. Above and southward of the northern bottom water is transition water with moderate property gra-

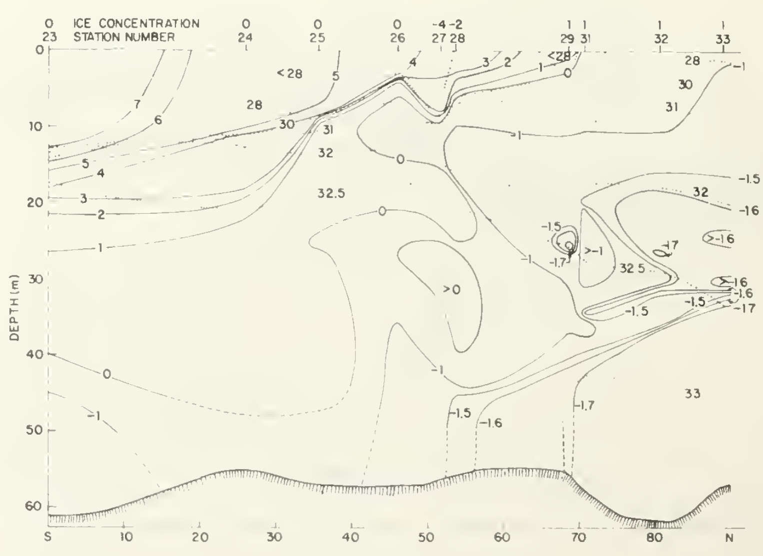

Fig. 15. Temperature and salinity cross section from the westernmost line of stations in MIZPAC 1974 (Figure 5) showing the wedge-like nature of the lower-layer front. Temperature fine structure is imbedded in the transition water near stations 27, 30, and 31. Ice concentrations as in Figure 11.

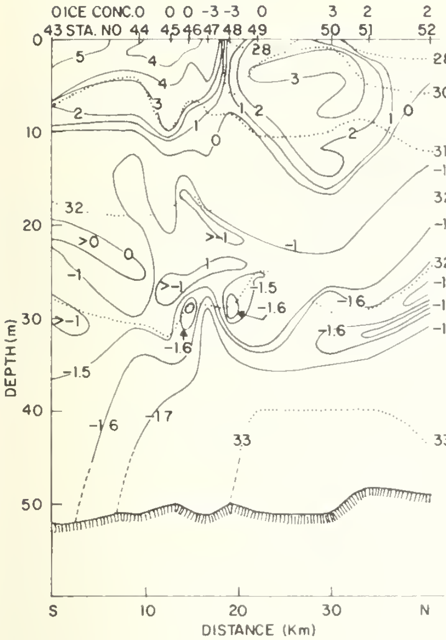

Fig. 16. Temperature and salinity cross sections, MIZPAC 1974, from the line of stations approximately 100 km east of those in Figure 15 illustrating temperature fine structure above the contorted wedge-shaped lower-layer front. Ice concentrations as in Figure 11.

dients and temperature contours complexly contorted by the imbedded finestructure.

We have perhaps six examples of fronts which clearly have the wedge shape. Others in this class are immensely complicated. The northern bottom water may not be continuous with its parent water to the north, the front may be more abrupt than suits the description 'wedge,' the $-1.6°C$ isotherm may not conform well to the $-1.7°C$ isotherm, and sometimes the fine structure is not there and vertical stratification is fairly well established.

Wedge-like fronts of ideal shape are perhaps more widespread than our sampling indicates. In retrospect, we find that the characteristic locations in which these fronts occur have not been sectioned frequently with the proper orientation. Adding to the difficulty of identification are the failure to sample all the way to the sea floor prior to 1977, the fact that the shape of the $-1.6°$ and $-1.7°C$ isotherms may be altered considerably by small instrumental errors and the possible nonuniform distribution of isotherms between stations where interpolation is subjective.

It will be noted that the sections of Figures 15 and 16 are on the flank of the ACC. Other examples occur on the flanks of the embayment at 168°W in 1978. We propose that this type of front is produced by a current running parallel to the ice face and to the northern bottom water. The flows and lateral shear are reasonably large, and lateral turbulence erodes the northern bottom water and mixes it with the southern water. Since velocities near bottom are least, erosion of the northern bottom water here is least and its bottom tip extends outward closest to the rapid stream. At middepth the higher shears erode more extensively leaving a general wedge-like shape rising toward the under-ice direction. The larger scales of lateral turbulence, variations in the bathymetry, movements of ice and water by the wind, and internal wave motion combine to shape the interface with great variety.

Temperature fine structure is not always present in a wedge-like front, and it exists in other locations than those in which fronts have been demonstrated. In part this may be due to finding fine structure where the station distribution does not yield cross sections suitably oriented to demonstrate the fronts. Also, we believe that fine structure is likely present throughout the transition water and need not always be confined to a zone close to the sharper aspects of the frontal boundary.

CONCLUSIONS

The ice melt-back pattern in summer in the Chukchi Sea may be taken as an indicator of the branching of the generally northward flow of warm southern water. The flows indicated by the melted-out bays are closely correlated with troughs in the bathymetry which supports the concept of bathymetric steering.

Two systems of fronts occur in the vicinity of the ice. One is found in the upper layer, generated at the interface between the ice and the oncoming warm water. The other is in the lower-layer between the resident winter bottom water and a water transitional between it and summer water. Both of these fronts are close together where the current shears parallel to the ice with low to moderate lateral mixing. Where the current impinges normal to the ice, for instance in the bays, the two fronts may be widely separated. On the flanks of rapidly moving streams wedge-like frontal interfaces in the lower layer are likely to be found. At ice peninsulas, where lateral turbulence is minimal, the upper and lower fronts coincide and the slopes in the lower-layer are steep. Temperature fine structure often is associated with the wedge-like fronts but also may be present elsewhere in the transitional zone between northern and southern water.

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